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Estimating long-term cliff recession rates from shore platform widths

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Abstract

Coastal cliff erosion is a problem in many coastal areas. However, often only very limited data are available to quantify the rates of recession for the development of coastal management strategies. In the soft flysch deposits of the Waitemata Group, Auckland, New Zealand, coastal cliffs are associated with shore platforms. Two models exist for the profile evolution of shore platforms and associated cliffs: the first suggests that an equilibrium profile develops in response to erosive processes, and this profile subsequently migrates landward; the second model suggests that the seaward margin of the shore platform is relatively static, and the profile extends landward through a combination of cliff recession and platform lowering. Physical simulations and field measurements for mudstone and limestone lithologies indicate that the second model is more likely for soft flysch deposits. A eustatic sea-level curve for the Weiti Estuary, Auckland, suggests that up to 7120 ± 70 years have been available for shore platform development since sea level reached the present seaward margins of shore platforms. Shore platform widths were measured using GPS at two sites in Waitemata Group rocks: the North Shore of Auckland; and the southern side of the Tawharanui Peninsula, North Auckland. The long-term cliff recession rates estimated from shore platform widths (1.4 ± 0.1 to 14.3 ± 0.1 mm y^{-1}) are consistent with the lower end of the average range of cliff top and face recession rates published for Waitemata Group rocks using different methods (11–75 mm y^{-1}), and in agreement with cliff base recession estimates (~3.5 mm y^{-1}). Shore platform widths were qualitatively related to the rock mass characteristics of the associated cliffs, and therefore platform widths could provide a method of identifying regions of potential hazard.

Keywords: Coastal erosion; Cliff erosion; Mass wasting; Rock mass characteristics; GPS; Slope stability

1. Introduction

Coastal cliffs are a major component of ~80% of the world's shorelines (Emery and Kuhn, 1982), and they are a major feature of the coast within the Auckland metropolitan area, New Zealand (Moon and Healy, 1994). Along the Auckland coast these include 10–30 m high cliffs developed in sedimentary rocks (e.g. Waitemata Group) and volcanic rocks (basalt lava flows), and lower 0–5 m high banks developed in cohesive sediments and soils. In many parts of Auck-

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land, development has occurred up to the cliff and bank edges, so that erosion poses a risk.

In order to determine the magnitude of cliff erosion hazard it is necessary to predict the landward extent of cliff edge translation over a specified planning period. This prediction is complicated for coastal cliffs because cliff erosion is a combination of relatively steady small incremental losses, and episodic rapid larger losses (Hall, 2002). Further, cliff erosion may exhibit large spatial variability so that an assessment of erosion at one location may have limited application beyond that site (Runyan and Griggs, 2003).

The rate of cliff erosion may be determined by dividing the historical extent of cliff recession by the time period over which erosion occurred. Episodic large failures can distort this assessment (Hall, 2002; Runyan and Griggs, 2003), so that most methodologies attempt to separate the long-term trend from the extent of episodic events (viz. Glassey et al., 2003). This requires a sufficiently long period of observations in order to be able to separate the two, and to ensure that the magnitude of episodic events has been reliably captured.

Previous studies have attempted to characterize erosion rates for Waitemata Group rocks around Auckland (Brodnax, 1991; Gordon, 1993; Moon and Healy, 1994). These studies demonstrate that for the Auckland region, the available historical record is too short to be able to reliably estimate the long-term cliff erosion rate. In this paper, the widths of shore platforms associated with Waitemata Group sedimentary rocks are assessed as a potential measure of long-term erosion rates.

2. Background

2.1. Shore platform development

There are two main theories for the profile evolution of shore platforms (Fig. 1): an equilibrium approach where the entire shore platform migrates land ward at a rate controlled by the recession of the associated coastal cliffs (Challinor, 1949; Trenhaile, 1974); and alternatively a static model that sees the seaward margin of the shore platform remaining relatively fixed, so that the platform width increases over time (Sunamura, 1983; Trenhaile, 2000, 2001). The equilibrium model is largely driven by wave-induced erosion, which acts at much the same rate everywhere on the platform. In contrast, wave erosion plays a minor role in the static model, with subaerial processes acting on the cliff dominating platform development.

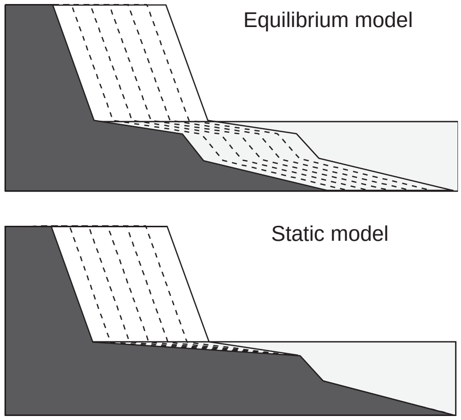

Fig. 1. Schematic diagram of the equilibrium and static models for the evolution of shore platforms.

Investigations into coastal cliff recession rates in a range of materials have found little correlation with available wave energy, but strong correlations with the strength of the cliffs (viz. Benumof and Griggs, 1999; Benumof et al., 2000; Budetta et al., 2000; Jones et al., 1993) or climatic factors such as rainfall (viz. Emery and Kuhn, 1982; Griggs and Brown, 1998; Lahousse and Pierre, 2003). There are many rating systems used to classify the strength of rock masses (Bieniawski, 1989; Romana, 1993), which consider the contributions from factors such as the intact strength of the rock, the characteristics of discontinuities in the rock mass, and water content. Selby (1993) considers the relative contribution of these factors to slope stability (Table 1).

Table 1
Summary of the rock mass characteristics affecting slope stability, and their relative contribution as reported by Selby (1993)

Factor	Contribution
Intact rock strength	20%
Discontinuity characteristics	
Spacing	30%
Orientation	20%
Width	7%
Continuity & infill	7%
Water	6%
Weathering	10%

It is evident that many factors may contribute to cliff erosion, and hence shore platform development. We consider that while weaker materials may be more responsive to wave processes (viz. Sunamura, 1983), shore platform development in harder materials is more a consequence of subaerial erosion and strength characteristics of the rock mass (viz. Lahousse and Pierre, 2003; Runyan and Griggs, 2003; Stephenson and Kirk, 2000). Weak materials behave more like unconsolidated beaches, and therefore are more consistent with an equilibrium profile development. Harder materials maintain a relatively fixed offshore platform margin, and therefore develop increasing platform widths with time.

Limited data have been published for harder materials (Stephenson, 2000). However, data do exist for flysch sequences at Kaikoura Peninsula, South Island, New Zealand (Stephenson and Kirk, 1996). These data indicate clearly that the seaward margin of the shore platform has been relatively stable during the development of the shore platform, and that the maximum erosion rates on the shore platform occur near the base of the cliff at 0.6–0.9 m above mean sea level, with negligible erosion occurring at the seaward margin. Further, it was demonstrated that subaerial processes dominated in the development of the shore platform and the recession of the associated cliffs (Stephenson and Kirk, 2000).

Therefore, we assume that the flysch sequences of the Waitemata behave in a similar fashion. Specifically, the seaward margin of the shore platform remains relatively static (undergoing negligible erosion) while the cliffs retreat and the platform widens. Hence, the platform width is a direct measure of the amount of cliff recession during the development of shore platform. We further assume that shore platform development only occurs while mean sea level corresponds roughly (± 1 m) to the mean elevation of the shore platform, and that the shore platform is not polycyclic as a consequence of subaerial processes developing a stable hillslope during the previous glacial. If these assumptions are valid, combining the platform width with the time available for platform development will provide an estimate of the long-term cliff recession rates.

Gibb (1986) analysed sea level trends at 8 locations around New Zealand, including the Weiti River located near Auckland. Based on radiocarbon dating of shell material associated with cheniers at the mouth of the river, he reported a calibrated calendar date of 71 20 ± 70 BP for the establishment of sea levels close to the present level. This is consistent with the average calibrated calendar date for culmination of the Flandrian transgression around New Zealand of 7300 ± 100 BP (Gibb, 1986). Although sea level has fluctuated since that time, the fluctuations were small and we assume that shore platform development was little affected.

Gibb (1986) noted that the Weiti River site showed no evidence of tectonic land movement during the Holocene. This is consistent with investigations into the seismic risk of the region, which identified only one fault that shows evidence of Holocene movement in the Auckland region, and this is located to the south and inland of the North Shore site (Edbrooke et al., 2003). For the purposes of calculating recession rates we have assumed that shore platform development has occurred for 7120 ± 70 years and that both study regions were unaffected by tectonic movements during this period.

2.2. Cliff recession rates

There have been several previous studies that have assessed the cliff recession rates for coastal cliffs in Waitemata Group rocks around the Auckland region. These studies have used a variety of methods to estimate the long-term recession rates (Table 2):

- Aerial photographs (Brodnax, 1991; Glassey et al., 2003). These studies have considered aerial photographs between 1940 and 1980, with the second being a re-evaluation of the first;
- Cadastral surveys between 1920 and early 1990s (Glassey et al., 2003);
- Location of dated structures constructed since 1926 (Brodnax, 1991; Glassey et al., 2003; Gordon, 1993; Moon and Healy, 1994; Paterson and Prebble, 2004);
- Geologic/geomorphic markers such as paleo-valley widths (Glassey et al., 2003; Paterson and Prebble, 2004);
- Shore profile surveys (Glassey et al., 2003);
- Cliff face surveys (Gulyaev and Buckeridge, 2004); and

Table 2
Long term recession rates for coastal cliffs in Waitemata Group rocks derived by various studies around Auckland, and the results of this study

Source	Method	Time period (y)	Range (mm y^{-1})	Average (mm y^{-1})
Brodnax (1991)	Aerial photographs	40	30–350	180
Gordon (1993)	Dated structures	60–70		3.5
Moon and Healy (1994)	Dated structures	60–70	20–60	
Glassey et al. (2003)	Aerial photographs	40	5.3–50.7	16.8
	Cadastral surveys	70–75	50–100	75
	Dated structures	60–70	0–81.8	33.4
	Geological markers	~6500	6–31	19
	Laser surveys	5–10		15.6
	Average of all methods		11–75	30.7
Paterson and Prebble (2004)	Dated structures	70–80	26–127	62.7
	Geological markers	~6500		111
	Shore platform width	~6500		31
Gulyaev and Buckeridge (2004)	Laser surveys	2	10–33	24 ± 7
North Shore site	Shore platform widths	7120 ± 70	1.4–14.3 ± 0.1	8.0 ± 0.3
Tawharanui Peninsula site	Shore platform widths	7120 ± 70	1.8–13.8 ± 0.1	5.3 ± 0.1

- Spot shore platform width measurements (Paterson and Prebble, 2004).

The recession rates determined by these studies are considered below. However, with respect to long-term erosion rates, most of these studies are potentially biased by the short duration of the available record, and the tendency to concentrate on regions with the highest recent erosion rates. Further, most of these studies have measured cliff recession from changes in the location of the top or face of the cliff. We suggest that for long-term recession, the location of the base of the cliff is more appropriate; since if the cliff base is static the cliff will eventually achieve a stable slope, and if the recession of the cliff base is high, then the stability of the cliff will decrease.

3. Methods

A Garmin eTrex 12-channel hand-held GPS unit was used to map the location of the seaward and cliff base margins of the shore platform between Tipau Point and Waiake Beach, on the North Shore, Auckland (Fig. 2A). The shore platform is developed in Waitemata Group rocks, with a range of mass strengths, on an east-facing low energy open coast (average wave climate of $H_s < 0.7$ m, $T \approx 7$ s). Cliff slope angles are 70°–75° and cliff heights vary from 5–20 m, with an average height of 12 m (Moon, 1984). A second survey was conducted 36 km further north, between Millon Bay and Prospect Bay on the southern coast of the Tawharanui Peninsula (Fig. 2B). The shore platform at this site is also developed in Waitemata Group rocks, but on a southwest facing very low energy coast (average wave climate of $H_s < 0.3$ m, $T < 5$ s). The cliffs have a similar morphology to those at the North Shore site, but are lower, with heights varying from 3–10 m, are less developed, and have a greater cover of vegetation (Fig. 2). Wave data for both sites were obtained from unpublished wave measurements using InterOcean S4ADW and DOBIE wave recorders by students from the Earth Sciences Department, University of Waikato.

Mapping was undertaken in autumn 2003 during fine, calm weather at low spring tide in order to get the best exposure of the seaward margin, and involved walking/wading along the coast as close to the seaward margin as possible, and then returning along the cliff base. Waypoints were stored to mark locations of particular interest. Although the eTrex can be used in DGPS mode, this was not done as it would have entailed carrying a radio receiver to obtain the DGPS corrections, and it was considered the chance of accidental immersion was too high. With Selective Availability (SA) turned off, if was found experimentally that while stationary the eTrex had a horizontal RMS error of 3.8 m for absolute positions, giving an error of ± 5.4 m for distances. When walking, the eTrex software filters the positions it calculates every second, which reduces the errors. This study is based on relative positions; when measurements were collected over a relatively short period (~1 h), comparisons between

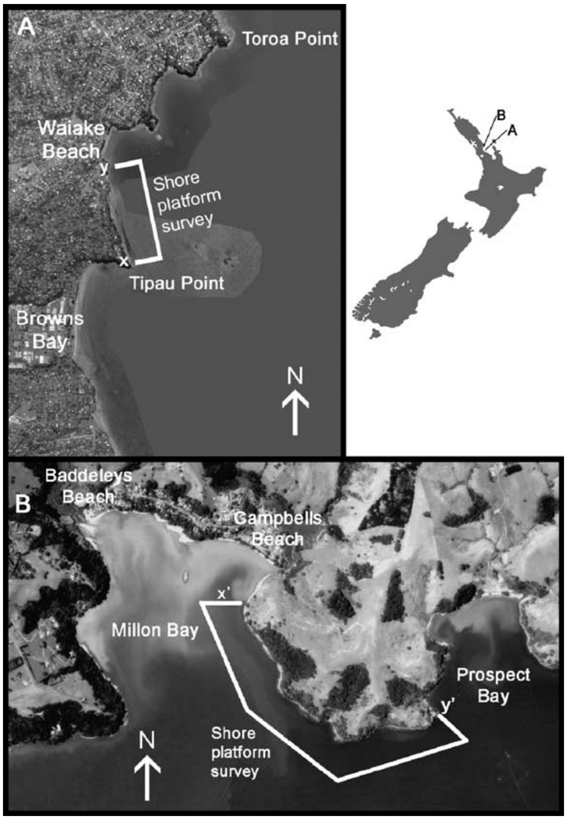

Fig. 2. Orthophotos of the shore platform survey sites: A) 750 m of shore platform between Tipau Point (x) and Waiake Beach (y), on the North Shore, Auckland; and B) 1150 m of shore platform between Millon Bay (x') and Prospect Bay (y'), on the southern coast of the Tawharanui Peninsula.

distances determined by GPS and tape measure differed by <2 m. For the purposes of error analysis, the GPS RMS error of ± 5.4 m was assumed, which probably over-estimates the actual measurement errors. The elevation data were considerably less accurate, and were ignored.

After the shore platform had been traversed, the eTrex current track log and waypoints were downloaded to computer as soon as possible to ensure no data were lost from the current track log which has a maximum capacity of ~1200 points. The data were reformatted using Microsoft Excel, and analysed using Matlab. The analysis procedure involved determining the local strike along 20–30 m of cliff for each GPS location along the cliff base. An orthogonal was then projected offshore and the intersection with the seaward margin interpolated from the seaward GPS locations. The shore platform width was then determined from the coordinates of the cliff base and interpolated seaward margin. The final result was a shore platform width for each GPS location obtained along the cliff base.

The recession rate was determined for each GPS location by dividing the width by the maximum time available for shore platform development (7120 ± 70 years). The resulting recession rates were smoothed using a Stineman function to reduce some of the spatial variability resulting from longshore variations in shore platform width. Confidence limits for mean recession rates were estimated as twice the standard error (viz. Press et al., 1989).

4. Results and discussion

The calculated shore platform widths and smoothed recession rates for the two sites are shown in Fig. 3, and the calculated recession rates (before smoothing) are summarised in Table 3. At the North Shore site (Fig. 3A), the widths varied between 10 and 103 m, with a mean width of 57.6 m. There is a trend of decreasing platform width moving northwards from Tipau Point towards Waiake Beach. However, it is evident that there is considerable variation in width about the general trend. This variation is fairly regular, consisting of a saw-tooth pattern of embayments along the seaward margin of the shore platform. This is superimposed on larger-scale embayments in the position of the cliff base. The long-term cliff recession rates range from 1.4 ± 0.1 to 14.3 ± 0.1 mm y^{-1}, with a mean of 8.0 ± 0.3 mm y^{-1} (Table 3).

Between Millon and Prospect Bays on the southern side of the Tawharanui Peninsula (Fig. 3B), the shore platform widths varied between 12.9 and 99.1 m, with a mean width of 38.0 m. Apart from the greatest widths occurring immediately adjacent to Millon Bay, there is no clear trend in width along the coast. Once again, there is considerable variation in width along the coast. Taking the same time interval and assumed errors, the long-term cliff recession rates range from 1.8 ± 0.1 to 13.8 ± 0.1 mm y^{-1}, with a mean of 5.3 ± 0.1 mm y^{-1} (Table 3).

Table 2 summarises the recession rates determined by previous studies of coastal cliffs in Waitemata Group rocks. Most of the previous studies determined

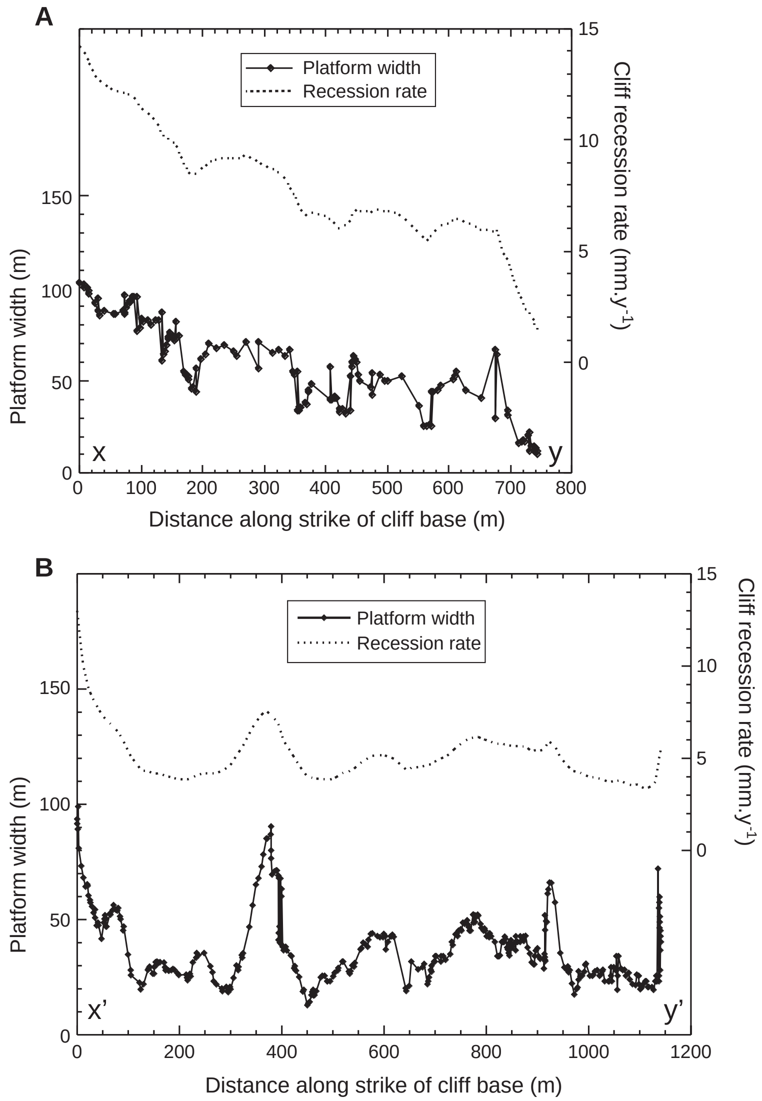

Fig. 3. Calculated shore platform widths and cliff base recession rates for the shore platform survey sites (Fig. 2): A) from Tipau Point (*x*) heading 750 m north towards Waiake Beach (*y*); and B) from Millon Bay (*x*′) heading 1150 m east towards prospect Bay (*y*′). The distance along the coast is the projected position of the cliff base GPS locations along the strike of the cliffs. The widths have been converted to cliff base recession rates, assuming 7120 years of development, and then smoothed with a Stineman function.

erosion rates over short periods, the shortest being 2 years for the laser surveys of Gulyaev and Buckeridge (2004). Glassey et al. (2003) reviewed and re-analysed all the available recession rates and concluded that the typical range of rates was 11–75 mm y^{-1}, with an average of 30 mm y^{-1} and localised maxima up to 100 mm y^{-1}. The recession rates estimated from shore platform widths are at the low end of rates estimated from short-term data. The data from Gordon (1993) were obtained for measurements of the cliff base relative to structures located on shore platforms, and is within the range of rates determined by this study. Examination of the data used by the previous studies suggests that the data are biased towards measurements at sites dominated by very weak materials, such as fault gouge or weathered material (viz. Pater-

Table 3
Univariate statistics for the raw cliff recession rate (mm y^{-1}) determined for the North Shore and Tawharanui Peninsula sites

	North Shore	Tawharanui Peninsula
Number of values	141	369
Mean	8.00	5.28
Median	7.69	4.75
Minimum	1.39	1.79
Maximum	14.25	13.76
Standard deviation	3.39	2.17
Standard error	0.29	0.11
Variance	11.49	4.69

son and Prebble, 2004), particularly where rapid retreat of the cliff top is occurring. Although there are minor variations in wave climate between the locations analysed by previous studies, the considerable variation at each location suggests that the reported erosion rates are likely a reflection of the rock mass characteristics.

Comparing only the recession rates determined in this study, the range of values at the two sites is similar (Table 3). However, at the 99.99% confidence level, an unpaired Student's *t*-test reveals that the mean recession rates are significantly different. The variances of the two sets of measurements (Table 3) are also significantly different at the same confidence level. Although there are slight differences in the wave climate, the high variability of recession rates within each site suggests that the recession rate varies in response to the characteristics of the Waitemata Group rocks exposed in the cliffs and shore platforms.

The North Shore site displays a wider range of lithologies than the Tawharanui Peninsula site, which consists almost entirely of flysch sequences with dominant massive sandstone units (1–2 m thick). The geology and rock mass characteristics of the North Shore study area have previously been described by Moon (1984). Two main geological units are present (Fig. 4): tuffaceous grit (Parnell Grit) at the northern end of the section; and a flysch sequence of alternating sandstone and mudstone beds for the rest of the sequence. Sandstone beds have very low unconfined compressive strength (<7 Mpa (de la Mare, 1992)), bedding planes inclined at 2°–6° S–SE (out of the cliff face), and 0.5–1.0 m joint spacing (Moon, 1984).

The widest shore platforms at the North Shore site, and hence greatest calculated recession rates (11.0–14.3 mm y^{-1}), occur near Tipau Point (A, Fig. 4) where a high proportion of shattered mudstone (mudstone beds are 1–1.5 m thick with intervening 0.3–0.5 m sandstone beds) leads to rapid removal of this material by subaerial processes (wetting/drying, wind erosion), and subsequent fall of overlying jointed sand stone blocks as support for these is removed. As the proportion of mudstone decreases in the flysch materials, there is a general trend of decreased shore platform width; near the northern end of the section (B, Fig. 4) narrow shore platforms (recession rates of 3.5 mm y^{-1}) correspond to the thinnest mudstone beds (<0.1 m) intercalated with relatively thick (0.8–1.2 m) sandstone beds. The widest shore platforms at the Tawharanui Peninsula site also occur in zones with the thickest mudstone units.

The narrowest shore platforms at the North Shore site (and hence lowest calculated recession rates of 1.4 mm y^{-1}) are associated with the relatively coarse-grained, non-jointed Parnell Grit at the northern end of the section (site C, Fig. 4). These have ~12 MPa unconfined compressive strength (de la Mare, 1992). These rock mass properties impart a greater mass strength than in the jointed flysch materials, and hence the grit is resistant to mass wasting processes. Parnell Grit is not a significant component of the Tawharanui Peninsula site.

Superimposed on the observed trend of increased recession rate with increased mudstone content, is the effect of structures within the flysch materials, particularly faulting. Cliff sections that appear relatively free of major discontinuities coincide with narrower sections of shore platform. Site D (Fig. 4), for example, is a structurally very simple area, and low recession rates (4–5 mm y^{-1}) are calculated for this area. Most of the Tawharanui Peninsula site is structurally simple, which is reflected in the median recession rate of 4.8 mm y^{-1}.

In contrast, a sudden increase in recession rate is seen at site E on the North Shore, where a number of intersecting faults running approximately normal to the strike of the present cliff can be seen (Fig. 4). The displacement along these faults is large (greater than the cliff height), and there is a wide zone of shattered rock along the fault surface, resulting in a very low mass strength. The faults extend across the shore platform, and are likely responsible for the highly variable platform width in this area. Observations in 1983 (Moon, 1984) suggested that these faults form

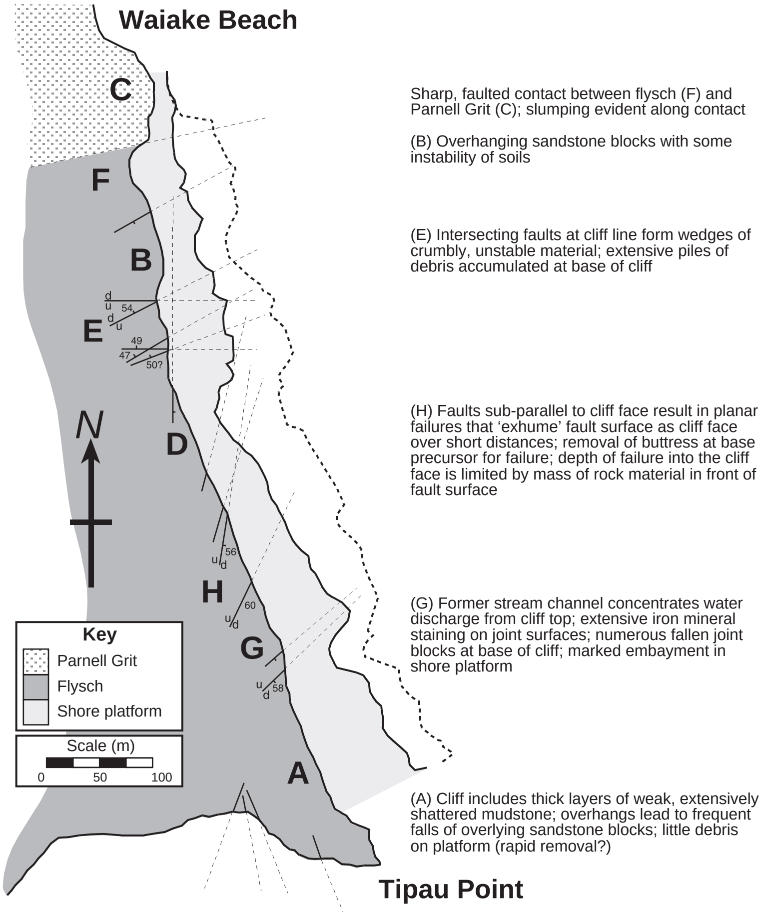

Fig. 4. Map of major rock units and structural controls on cliff stability between Tipau Point and Waiake Beach, North Shore, Auckland. The blue shaded area represents the measured shore platform, and the offset dashed curve is the calculated shore platform width. Descriptions of the major features influencing cliff stability and platform width are given.

wedges of crumbly, unstable material with extensive debris deposits at the base of the cliff. This evidence of rapid cliff erosion within this jointed zone is in keeping with calculated high rates of recession across this zone (8.8 mm y^{-1}).

Likewise, the contact between the flysch and Parnell Grit (F, Fig. 4) units is marked by a sharp boundary, which is likely a depositional contact with later fault movement along it. As a result, a wide band of frittered mudstone exists along this contact. Loose mudstone talus covers much of the cliff face south of this contact, indicating rapid erosion. This corresponds with an embayment in the cliffs, and a consequently wider shore platform. Calculated recession rates decrease sharply heading northwards across this contact (~700 m from Tipau Pt in Fig. 3A).

At site G a minor stream channel is evident in the geomorphology above the cliff. The trend of this channel intersects the embayed margin of the shore platform evident north of Tipau Point (Fig. 4), which is interpreted as representing a small stream valley at times of lower sea level. Therefore, it is possible that some of the smaller scale shore platform width variations have been inherited from the existing topography at the culmination of the Flandrian transgression. This is clearly the case for the larger-scale bay-headland morphology along the North Shore coast. As the stream has been unable to incise the cliffs at a rate concomitant with the erosion rate of the cliffs, the pre-existing embayment appears to result in a reduced cliff recession rate (6.4 mm y^{-1}).

At site H (Fig. 4) the calculated recession rates are 8.9–9.7 mm y^{-1}, which are less than the maximum rates at Tipau Point (11–14.3 mm y^{-1}). Despite the lower recession rates, observations show that significant planar failures in the cliff result in undercutting of structures (Moon, 1984). The observed failures occur along faults running approximately parallel to the cliff-face, with failures progressively exposing the fault plane. These faults have been exposed relatively recently in the development of the shore platform. This suggests that the recession rate should be accelerating and that the long-term rate is an under-estimate. Further, these failures illustrate that episodic events may cause significant departures from the long-term trend. Hence, estimates using the shore platform width should be supplemented by site investigations to identify potential failures.

If some zones of narrow shore platform are inherited from pre-existing topography (i.e. before the coastal cliffs existed), the possibility also exists that the shore platforms are polycyclic and represent reactivated cliffs from the previous interglacial (viz. Trenhaile, 2002; Trenhaile et al., 1999). Although, mass wasting processes drive cliff erosion along this section of coast, it is also evident that waves play an important role in removing the debris from the shore platform. Areas regularly exposed to wave activity are relatively debris free, while talus cones have accumulated where wave action is infrequent. If debris accumulates at the base of the cliffs, their stability increases greatly (Moon and Healy, 1994), and examination of slopes in similar materials isolated from wave activity indicates that stable slopes are achieved relatively quickly (decades to hundreds of years). Therefore, we do not consider it likely that shore platforms at either of the sites developed from pre-existing older platforms at the culmination of Flandrian Transgression. Instead, they are wholly Holocene features.

Overall, unless the shore platforms and associated cliffs are polycyclic, the potential errors all produce an underestimate of the long-term cliff recession rate. Polycyclic shore platforms are likely to be significantly wider than could be produced by Holocene processes, and hence would over-estimate the long-term recession rate. Since the rates determined for the two sites are lower than those determined by most other studies (Table 2), we are confident that our original assumption that the shore platforms are wholly Holocene is justified. Further, we consider that the recession rates determined by this method represent a suitable lower bound on the long-term recession rates for the Waitemata Group rocks.

5. Conclusions

Shore platform widths measured by GPS provide a quick method for assessing long-term coastal cliff recession rates. The resulting average recession rates are unaffected by the episodic nature of coastal cliff recession, and have a high spatial resolution due to the sampling rate of the GPS. However, this study also identified that coastal cliff erosion is strongly affected by mass wasting processes and there is likely to be significant spatial variation. Therefore, cliff recession rates predicted by this method should be supplemented by site investigations to assess local rock mass characteristics (or slope stability) if coastal recession would adversely impact infrastructure and the public. This is particularly important if cliff recession rates are a component of any calculation of coastal hazard zones or development setback.

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